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Thin Film, Concentrator and Multijunction Space Solar Cells—Status and Potential

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THIN FILM, CONCENTRATOR AND MULTIJUNCTION SPACE SOLAR CELLS - STATUS AND POTENTIAL

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SUMMARY

Recent, rapid advances in a variety of solar cell technologies offer the potential for significantly enhancing, or enabling entirely new, mission capabilities. Thin film solar cells are of particular interest in that regard. A review is provided of the status of those thin film cell technologies of interest for space applications, and the issues to be resolved before mission planners can consider them. A short summary is also given of recent developments in concentrator and multijunction space solar cell and array technology.

INTRODUCTION

The range of future new mission opportunities continues to expand for both the U.S. civil and military space programs. Concomitant with that expansion is a growing requirement for a broader spectrum of space power system technology options that can be more precisely tailored to meet a specific set of mission requirements. The paragraphs that follow will discuss some of the important emerging new cell technologies, their potential payoff, and the issues that remain unresolved before each can be successfully used in space.

THIN FILM CELLS

It has been axiomatic that high efficiency is the chief attribute sought of photovoltaic space power systems by mission planners, given that key reliability requirements are met first. The reasons for requiring high efficiency vary, and are dependent on both mission environment and array configuration. The usual result is that array size is restricted, placing a premium on cell efficiency. The area may be restricted because the array is body mounted, or, for deployable arrays, because on-board fuel storage is limited. The latter is important for momentum management and/or drag make-up (depending on the orbit), and strongly affects the on-orbit lifetime of the satellite. Other attributes such as radiation resistance, low mass and thermal cycle survivability have a greater or lessor degree of importance, depending on specific mission requirements.

Future mission requirements may well cause the traditional relative priorities of efficiency, radiation damage and mass to change, particularly as interest grows in establishing an infrastructure to support manned missions to the surface of the moon and Mars. Power systems for surface operations place a new emphasis on low mass and transportability, or stowability, for the solar arrays. An additional element of the infrastructure required to support such missions is likely to be a system of cargo vehicles using electric propulsion. The contending power sources are solar arrays and nuclear reactors. Given the large power requirements expected, the end of life (EOL) specific power of the arrays becomes a dominant concern. Some early estimates are that EOL specific power must exceed 100 W/kg for at least one round trip from LEO to beyond the van Allen belts and back. The choices of LEO parking orbit and dwell time become critical in determining the most appropriate cell and array technologies to consider, and it now appears that system studies must trade ultrahigh EOL specific power carefully with array area when seeking to achieve optimum mission capability.

Although the thin film cells do not appear able to achieve efficiencies that compete with advanced, single crystal solar cells, they offer the potential for extremely high specific powers and low cost manufacturing techniques. The key technology issue is direct, monolithic fabrication of the cells and interconnects on space qualified, flexible substrates. There are at present three thin film cells of interest: amorphous silicon (a-Si), copper indium diselenide (CIS), and cadmium telluride (CdTe). Of these, only amorphous silicon has been fabricated in appreciable quantity on flexible substrates of any sort. Materials used with various degrees of success include thin stainless steel and polyester sheet (ref. 1), polyethylene terepthalate (ref. 2) and polyamide (Kapton) (refs. 3 and 4). Even though thin, the stainless steel substrate is still too heavy to yield high specific power blankets and is not of further interest in this discussion. Of the non metallic substrates, only the polyamide (Kapton) has been used in space solar arrays and has been shown to avoid degradation from the intense ultraviolet light in the AM0 spectrum. Efficiencies of comparable cell structures on stainless steel and polyethylene substrates are essentially the same, and comparable to those achieved on glass, the substrate most commonly used for terrestrial applications. Efficiencies of cells on Kapton are somewhat less than on glass or stainless steel, although efforts to develop structures on Kapton are more recent than on the other materials.

There are a large number of possible structures for a-Si solar cells, and not all of them have been fabricated on each of the flexible substrates. In fact, because of the large number of different cell types based on amorphous silicon, care must be exercised when comparing their efficiency and radiation resistance. Many reports of high radiation resistance came from measurements made on early, low efficiency cells, primarily single gap, single junction structures. Table I illustrates the situation. There is as yet little or no data on the radiation resistance of the more advanced, higher efficiency a-Si solar cell structures. The inherent thinness of the active layers of single bandgap, single or tandem junction a-Si cells, coupled with the fact that minority carrier transport is dominated by electric field drift rather than diffusion, contributes in large measure to their observed high radiation resistance. However, higher efficiency structures will be thicker, since they are multiple bandgap structures that require more layers. The new layer materials have also not undergone extensive radiation damage testing, with the result that there is considerable uncertainty about the degree of radiation resistance to expect from these cells.

For the sake of brevity, not all of the possible a-Si cell types are listed in the table, nor are all the individual substrate types differentiated (e.g., rigid substrates include both stainless steel and glass sheet), while only the results for cells on Kapton are included in the flexible substrate category. The very long term goal is to achieve a monolithic, multiple bandgap (triple junction, triple gap) 18 percent AM0 efficient cell on a flexible substrate with radiation resistance equal to or better than the best high efficiency single crystal cells. Clearly such a goal is ambitious. The payoff will be an ultra-lightweight solar array blanket with the potential for an EOL specific power (after an equivalent fluence of 1×10^{17} 1-MeV electrons/cm^2) in excess of 1000 W/kg, and EOL area power densities above 150 W/m^2.

We do not have space to discuss the problem in a-Si known as the Staebler-Wronski effect (ref. 5), except to say that cell structures have recently been demonstrated in which it is limited to a 10 percent loss of power, compared to earlier values approaching 40 percent (ref. 6). Since it appears advantageous to have thin active layers in the cell to limit both Staebler-Wronski degradation and radiation damage, it is reasonable to expect that the multiple bandgap structure has a good chance of demonstrating excellent performance on both accounts.

Figure 1 shows an emerging section of a 50 μm thick, 33 cm wide Kapton ribbon that has been processed into a series of 30- by 30-cm amorphous silicon solar cell submodules in a roll-to-roll process. The cell structure produced is shown in figure 2. AM0 efficiencies approaching 5 percent have been achieved with the structure, although not as yet in the continuous processing technique (ref. 7). In a second approach, a Kapton film is laminated onto a thin stainless steel sheet and processed with the same techniques used to deposit and process a-Si directly on the stainless steel (ref. 8). After cell fabrication and interconnection are complete, the stainless steel is etched away, leaving a complete submodule in the form of a flexible, lightweight blanket. There are no radiation damage test results available for either submodule type. Although this work is very preliminary in nature, it does establish the feasibility of producing large area, monolithically fabricated, flexible amorphous silicon solar cells on Kapton. The next challenge is to fabricate tandem cells with efficiencies comparable to those achieved on glass substrates, followed by development of a suitable high efficiency cascade thin film solar cell.

CIS ($CuInSe_2$) cells on flexible, nonmetallic substrates have only recently begun to be investigated by NASA at the time of this writing, with the result that there is essentially no data to report. A related effort to deposit CIS cells on thin metal foils has been reported (ref. 9), but again, no efficiency or radiation damage data are available at this time. Radiation damage studies on CIS cells deposited on conventional glass substrates have shown superior resistance to 1 MeV electron radiation compared to the best single crystal cells of any type (ref. 10), and good resistance to proton radiation damage (ref. 11), as indicated in table I. There is no reported work on deposition on flexible substrates for any of the remaining cells listed in table I. They are included here because they offer the potential for higher efficiency than CIS cells, with the possibility that they could be incorporated in monolithically integrated, flexible, thin film submodules.

CONCENTRATOR ARRAY TECHNOLOGY

Figure 3 shows a 36 element submodule of an advanced space concentrator array concept now under development by NASA. A schematic of the basic conversion element is shown in figure 4. It consists of a unique, lightweight domed Fresnel lens (ref. 12) mounted over a high efficiency concentrator cell. Although the cell shown is a single junction, two terminal cell, multiple bandgap cells with multiple terminals could be used as well. This sort of technology transparency is one of the key features of the design, along with the potential for low cost. The latter derives from the fact that concentrator arrays require a greatly reduced area to be covered by expensive semiconductor devices than planar arrays of the same output. An equivalent area must be covered by the lenses, but they are made inexpensively out of low cost materials.

Table II provides a comparison of the estimated array parameters obtained when GaAs and GaAs/GaSb concentrator cells (ref. 13) are used for conversion. The potential exists for significant gains in both specific power and area power density with this technology compared to state-of-the-art planar silicon solar arrays. The projected specific powers are even competitive with those projected for the Advanced Photovoltaic Solar Array (APSA) under development by

NASA. The APSA is a flexible array design incorporating thin (62 μm) silicon solar cells mounted on a thin (50 μm) Kapton substrate (ref. 14); BOL specific power is 130 W/Kg.

The submodule shown in figure 3 has been designed to maintain essentially full output when the array is pointed off axis by up to $\pm1°$. The pointing accuracy tolerance can be increased up to $\pm4°$ with very little impact on array power. As shown in figure 5, on-axis array maximum power will decrease by less than 4 percent when the pointing accuracy tolerance is increased to $\pm4°$. A 12 element submodule incorporating $\pm2°$ pointing accuracy tolerance and the recently developed 30 percent tandem concentrator cell (ref. 13) is currently under development for a flight test in early 1993, as part of a broader evaluation of environmental effects on advanced solar cell and array technology (ref. 15). The flight test will determine the performance of a variety of advanced solar cell and array technologies in orbit. The data are expected to be useful not only for evaluating advanced array technology, but also for establishing acceptable levels for solar array operating voltages over a range of near earth orbits.

MULTIPLE BANDGAP SOLAR CELLS

No attempt will be made to summarize all the multiple bandgap solar cell types that have potential for space application. Candidates range from two junction, mechanically stacked, two or four terminal devices to monolithically grown three junction structures with a variety of interconnect configurations. They can be combinations of thin film and single crystal devices, and can be designed for either planar or concentrator operation. The key point is that there have been rapid and significant advances in the technology for producing such cells.

The ability to accurately measure the performance of multiple bandgap cells, however, has only recently begun to be addressed (ref. 16). Work recently performed at NASA's Lewis Research Center has clearly shown the need for extreme care with MBG cell measurements. Results of experiments performed in the NASA high altitude aircraft to obtain the full I-V curve and the temperature dependence of MBG cells at low air mass show conclusively that conventional laboratory techniques will be misleading (ref. 17). Figure 6 illustrates the point. The variation with temperature of the bandgap of the upper cell has a major effect on overall device efficiency, as does the spectral content of the incident light used in the testing. Conventional laboratory simulators are often too rich in the red region of their output spectrum, and can give misleading (usually high) values for the MBG device efficiency. Measurement of the correct temperature dependence of such cells in the incorrect spectrum is virtually impossible. Until more advanced laboratory light sources are available, high altitude measurement of the full I-V characteristic and temperature dependence of the test device will be the only way to obtain correct results.

CONCLUSION

A wide variety of potential space solar cell technologies are beginning to emerge, ranging from ultra-lightweight, flexible thin film submodules to advanced, high efficiency concentrator arrays using multiple bandgap solar cells. Blanket BOL specific powers exceeding 1000 W/Kg are now feasible, with only modest advances in thin film efficiency. The radiation resistance of all of the advanced, flexible substrate thin film cell technologies has yet to be fully determined, but early results from similar cell structures on rigid substrates are promising. Concentrator array BOL power densities exceeding 300 W/m^2 are also possible, with specific powers competitive with current lightweight array technology.

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TABLE I. - POTENTIAL THIN FILM SOLAR CELLS FOR SPACE APPLICATION

[All efficiencies estimated from AM1 and AM1.5 measurements.]

Cell type	Cell structure	Projected efficiency, percent	Laboratory efficiency, percent	Commercial efficiency, percent	Radiation resistance, P/Po	
					1×10^{15} 1 MeV, e-	1×10^{13} 1 MeV, p+
a-Si	Single junction, single gap on rigid substrate	10	<9.0	<5.0	0.80	0.65
a-Si	Tandem junction, single gap on rigid substrate	12	9.9	<5.0	----	0.75
a-Si	Tandem junction, single gap on flexible substrate	10	5.5	----	----	----
a-Si	Tandem junction, dual gap on rigid substrate	15	8.6	----	----	----
a-Si	Monolithic, multiple bandgap on rigid substrate	18	10.9	----	----	----
$CuInSe_2$	3 μm cell, 1 μm window on glass substrate	>13	10.4	----	1.00	0.65
$CuIn_xGa_{1-x}Se$	3 μm cell, 1 μm windown on glass substrate	>15	8.2	----	----	----
CdTe	Thin film on glass superstrate	>18	9.8	----	----	----
a-Si/$CuInSe_2$	Mechanically stacked tandem cell	>20	12.5	----	----	----

TABLE II. - MINI-DOME FRESNEL LENS CONCENTRATOR ARRAY PERFORMANCE ESTIMATES

[Measured performance parameters for prototype cells and lenses are underlined.]

Item	GaAs baseline	Tandem cell improved
Cell type	GaAs	GaAs + GaSb
Cell efficiency (25 °C), percent	24	24 + 8 = [a]32
Cell operating temperature, °C	80	80 and 80
Cell efficiency (operating temperature), percent	22	29
Lens efficiency, percent	90	[b]95
Packing factor, percent	97	97
Mismatch/wiring, percent	93	93
Array efficiency, percent	18	25
Power density (W/m^2), percent	**245**	**340**
Panel mass (kg/m^2)	2.4	2.4
Structure mass (kg/m^2)	0.7	0.7
Array mass (kg/m^2)	3.1	3.1
Specific power (w/kg)	**79**	**110**

[a]Current performance measured at 30 percent AMO, 25 °C.
[b]With addition of anti-reflection coating.

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Figure 1.—Flexible amorphous silicon photovoltaic blanket.

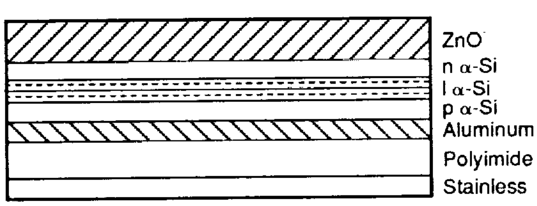

Figure 2.—Amorphous silicon cell structure on flexible blanket.

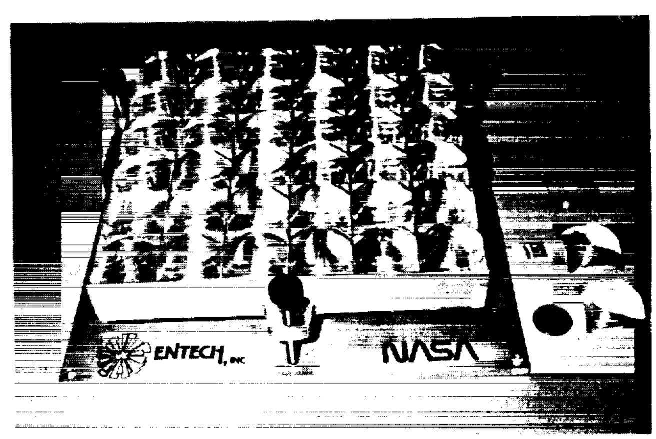

Figure 3.—High efficiency mini domed Fresnel lens concentrator submodule.

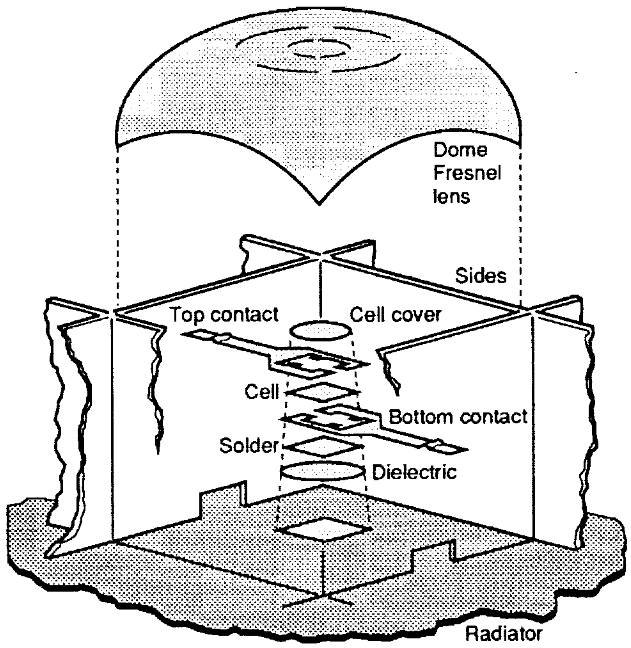

Figure 4.—Schematic representation of mini domed Fresnel lens/cell element.

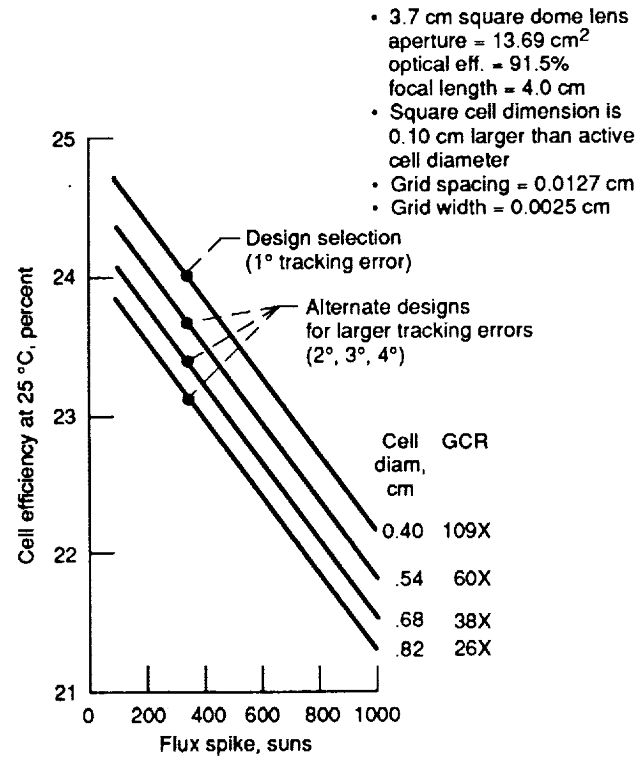

Figure 5.—Effect of cell size on tracking tolerance for refractive concentrator array.

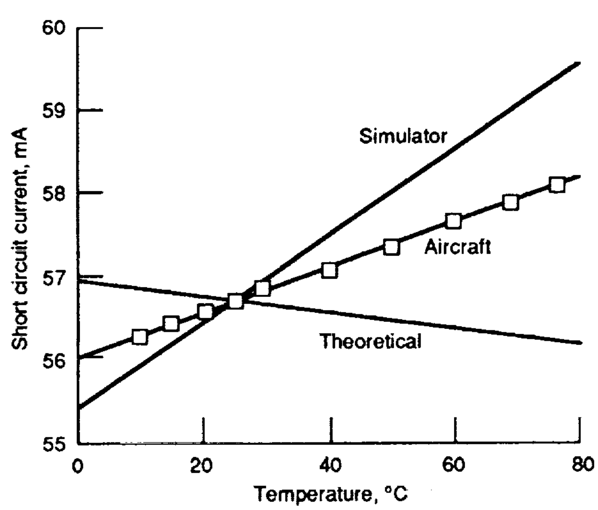

Figure 6.—Temperature of GaAs solar cell in AlGaAs-filtered AMO solar spectrum.

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